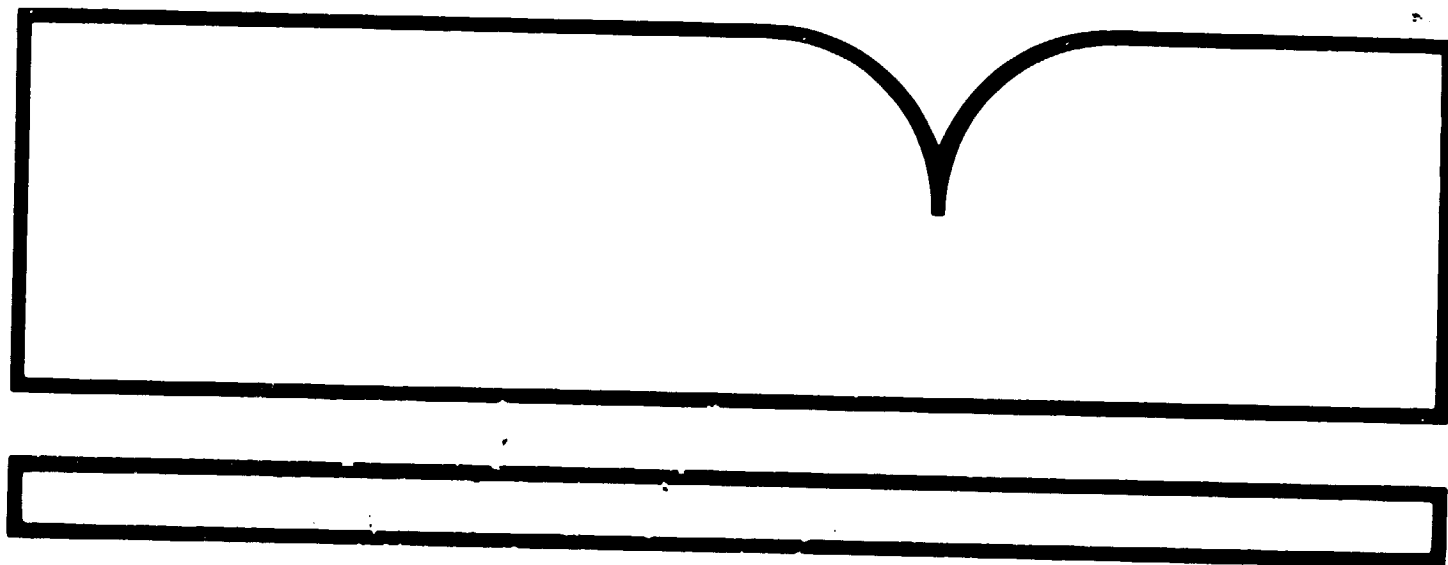Observations of Atmospheric Emission and
Attenuation at 20.6, 31.65, and
90 GHz by a Ground-Based Radiometer

(U.S.) National Oceanic and Atmospheric
Administration, Boulder, CO

Prepared for

Jet Propulsion Lab., Pasadena, CA

Nov 88

Abstract: During 1987 and 1988, ground-based zenith-viewing observations of atmospheric thermal emission were made at frequencies of 20.6, 31.65, and 90.0 GHz. At the locations of the experiments-San Nicolas Island, California, and Denver, Colorado-radiosonde observations of temperature and humidity were also available. The data, after conversion to attenuation by use of the mean radiating temperature approximation, were processed to derive attenuation statistics. Both clear and cloudy attenuation characteristics are examined and compared with results from most recent theories. The predictability and interdependence of the three separate channels are also examined. It is found that attenuation for any two channels can predict that of the third to within 25%.

NOAA Technical Memorandum ERL WPL-156

OBSERVATIONS OF ATMOSPHERIC EMISSION AND ATTENUATION
AT 20.6, 31.65, AND 90 GHz BY A GROUND-BASED RADIOMETER

E. R. Westwater
J. B. Snider
M. Falls

Wave Propagation Laboratory
Boulder, Colorado
November 1988

Stimulating America's Progress
1913-1988

noaa NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION / Environmental Research
Laboratories

OBSERVATIONS OF ATMOSPHERIC EMISSION AND ATTENUATION
AT 20.6, 31.65, AND 90 GHz BY A GROUND-BASED RADIOMETER

E. R. Westwater
J. B. Snider
M. Falls

NOTICE

Mention of a commercial company or product does not constitute an endorsement by NOAA Environmental Research Laboratories. Use for publicity or advertising purposes of information from this publication concerning proprietary products or the tests of such products is not authorized.

Contents

OBSERVATIONS OF ATMOSPHERIC EMISSION AND ATTENUATION AT 20.6, 31.65, AND 90 GHz BY A GROUND-BASED RADIOMETER*

E.R. Westwater, J.B. Snider, and M. Falls
NOAA/ERL/Wave Propagation Laboratory
Boulder, Colorado 80303

ABSTRACT. During 1987 and 1988, ground-based zenith-viewing observations of atmospheric thermal emission were made at frequencies of 20.6, 31.65, and 90.0 GHz. At the locations of the experiments—San Nicolas Island, California, and Denver, Colorado—radiosonde observations of temperature and humidity were also available. The data, after conversion to attenuation by use of the mean radiating temperature approximation, were processed to derive attenuation statistics. Both clear and cloudy attenuation characteristics are examined and compared with results from most recent theories. The predictability and interdependence of the three separate channels are also examined. It is found that attenuation for any two channels can predict that of the third to within 25%.

1. INTRODUCTION

Over the past decade,, the Wave Propagation Laboratory (WPL) has designed, constructed, and field-tested several ground-based microwave radiometers to observe the atmosphere (Hogg et al., 1983; Westwater and Snider, 1987). In particular, extensive experience has been gained by using both zenith-viewing and steerable dual-frequency instruments operating at 20.6 and 31.65 GHz. These instruments continue to provide unique and meteorologically useful observations of precipitable water vapor (V) and integrated cloud liquid (L). Perhaps equally useful, but certainly not as well studied, are the microwave attenuation characteristics that these devices can easily provide. Within the last year, WPL extended its radiometric capabilities by adding a channel at 90.0 GHz to the steerable and transportable radiometer. All three channels have equal beamwidths of 2.5°, point in the same direction from the same location, and hence are capable of simultaneously measuring emission and attenuation from the same volume of air. We present here examples of some of the data taken with the new system; from these data, several statistical and physical quantities, relevant to radio propagation studies, are derived and compared with theory.

2. DESCRIPTION OF EXPERIMENTS

2.1 San Nicolas Island, California, July 1987

In July 1987, WPL participated in an investigation of the characteristics of marine stratocumulus clouds at San Nicolas Island (SNI), located approximately 50 nautical miles west of Los Angeles. Zenith brightness temperatures were observed continuously by the WPL mobile, microwave radiometer operating at 20.6, 31.65 and 90.0 GHz. Although the primary purpose of the SNI observations was to study cloud properties, a secondary goal was to acquire statistics on attenuation by cloud liquid water, especially at 90.0 GHz. Supporting data for the attenuation measurements at SNI were provided by radiosondes launched up to several times daily and by standard surface meteorological observations.

Clouds were persistent during the 3-week measurement period, being present 76% of the time. The V was variable, ranging from about 0.9 to 3.1 cm and having a mean value of 1.9 cm.

2.2 Denver, Colorado, December 1987

The mobile three-channel radiometer was installed at the Denver (DEN) National Weather Service Forecast Office (NWSFO) in December 1987, where it operated alongside the WPL six-channel radiometer (Microwave Radiometric Profiler, MRP), which measures V, L, and temperature profiles. Supporting data were provided by the MRP, by the daily radiosondes released at standard times of 2300 and 1100 UTC, and by surface meteorological observations. Denver weather in December is characterized by relatively dry periods (V ≤ 0.5 cm) and occasional periods of snow. Clouds containing supercooled liquid water are common, especially just before and during precipitation.

In contrast to SNI, clouds were present only 15% of the time. The V was low, ranging from 0.1 to 1.0 cm and having a mean value of 0.5 cm.

2.3 Denver, Colorado, August 1988

The three-channel radiometer was operated continuously during August 1988. These observations were taken under typical Denver summer conditions; the V was variable (1.06–3.29 cm with a mean value of 2.03 cm), and liquid-bearing clouds were present 11.8% of the time. As in December 1987, supporting data were provided by the MRP, by NWS radiosondes, and by surface meteorological observations.

2.4 General

Radiometers are calibrated using the "tipping curve," that is, the elevation scan, method in which absolute absorption at each operating frequency is calculated from the slope of the relative absorption versus relative path length (air mass) measured as

the radiometer antenna is scanned in elevation (Hogg et al., 1983). Tipping curve calibrations are performed only during clear weather. The radiometer output at each operating frequency is related to the atmospheric brightness temperature T_b, calculated from the absolute absorption τ (in nepers) by

$$T_b = 2.75\, e^{-\tau} + (1 - e^{-\tau})T_{mr} \qquad (1)$$

where T_{mr} is a mean radiating temperature of the atmosphere and 2.75 is the cosmic background brightness (both in kelvins). T_{mr} is normally calculated from climatological radiosonde data and was done so for DEN, December and August. For SNI, however, T_{mr} was computed from the 69 soundings recorded during July 1987. The absorptions τ discussed in Sections 4 to 6 are presented in decibels and are computed from the measured brightness temperatures by

$$\tau(dB) = 4.343 \ln \frac{T_{mr} - 2.75}{T_{mr} - T_b} . \qquad (2)$$

Different humidity sensors were employed by the radiosondes at SNI and DEN. Soundings at SNI were made using Vaisala RS80 radiosondes with HUMICAP humidity sensors. At DEN, standard VIZ radiosondes with ACCU-LOK humidity sensors were employed. Accuracies of 2% are claimed by both manufacturers. However, to the authors' knowledge, a rigorous intercomparison of the two units has not been made.

Representative brightness temperatures measured simultaneously at each operating frequency are shown in Fig. 1 for SNI and DEN. The maxima and higher scintillation rates are associated with liquid-bearing clouds. Note the increase in brightness temperature at 90.0 GHz relative to 20.6 and 31.65 GHz as clouds pass through the radiometer antenna beam. Note also the higher brightness temperatures at all frequencies at DEN during August. This increase is due to high amounts of moisture.

3. ATTENUATION STATISTICS

The data were edited in several ways before statistics were computed. First, 24-h time series of all data were plotted and then visually inspected for the presence of outliers or questionable points. For DEN data, measurements at 20.6 and 31.65 GHz were also available from an adjacent radiometer; these also were used in visual editing. After the preliminary editing was completed, computer screening, based on approximately known physical relationships between the frequencies, was performed. This additional screening eliminated, for example, a segment of data in which snow on the antenna adversely affected the 90.0 GHz channel. After these stringent procedures were applied, there remained a total of 4805 5-min-average data for SNI (about 400 h), and 17,792 2-min-average data for DEN August (about 598 h).

The cumulative distributions (Figs. 2–4) are markedly different for all three data sets and for all three frequencies. These differences reflect climatic differences be-

- 3 -
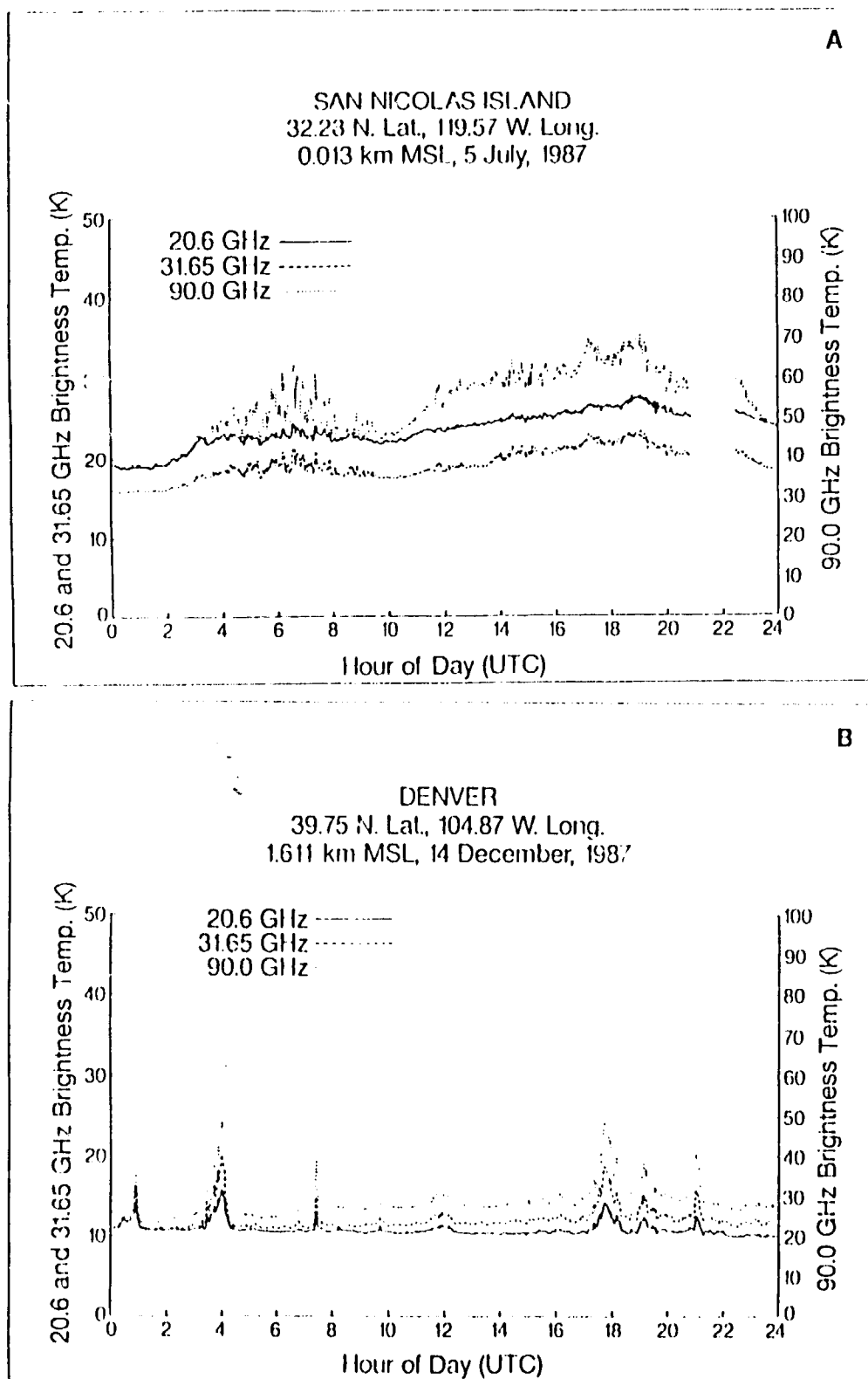
Fig. 1. Time series of brightness temperatures measured by a three-channel radiometer. (A) San Nicolas Island, California, 5 July 1987; (B) Denver, Colorado, 14 December 1987.
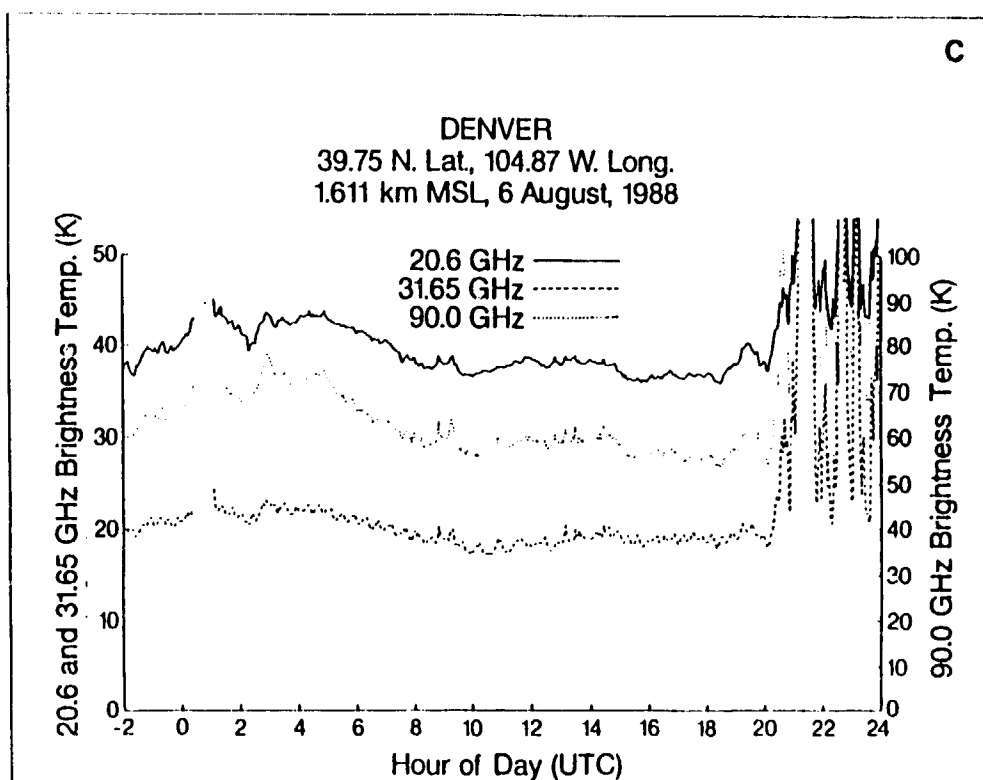
Fig. 1. (Continued) (C) Denver, Colorado, 6 August 1988.

tween the two locations and between the two seasons at Denver. First, the sea-level altitude of SNI always results in dry attenuation greater than that at DEN. Second, the mean humidity at SNI and at DEN August are roughly about a factor of 3 higher than at DEN December, resulting in a high absorption by vapor. The largest differences, however, were in cloud liquid: The marine stratocumulus clouds of SNI contained measurable liquid 76% of the time and were only rarely present at temperatures below 0.0°C; the winter clouds at DEN contained measurable liquid about 15% of the time and were frequently supercooled; the summer clouds at DEN were present roughly 12% of the time and, at times, contained much more liquid than those of SNI. Summer clouds in DEN frequently are cumulus and cumulonimbus types, both of which can contain large amounts of liquid.

4. CLEAR-AIR ABSORPTION; MODELING VERSUS EXPERIMENT

The dominant microwave absorption from atmospheric gases in the troposphere arises from water vapor and oxygen, and the modeling of this absorption over the frequency range of 1–1000 GHz has been extensively studied by Liebe (1985). For water vapor, Liebe's model uses the known properties of all H_2O spectral lines below 1000

Fig. 2. Cumulative distribution of zenith attenuation measured by a three-channel radiometer at San Nicolas Island, California, July 1987. Data consist of 4805 5-min averages.

Fig. 3. Cumulative distribution of zenith attenuation measured by a three-channel radiometer at Denver, Colorado, December 1987. Data consist of 14181 2-min averages.

90 GHz
Mean Absn. = 1.19 (dB)
Std. Dev. = 1.85 (dB)

Zenith Atten. (dB)

Percent of Samples

31.65 GHz

Freq. (GHz)	Mean Absn. (dB)	Std. Dev. (dB)
20.6	0.497	0.195
31.65	0.278	0.259

20.6 GHz

Zenith Atten. (dB)

Percent of Samples
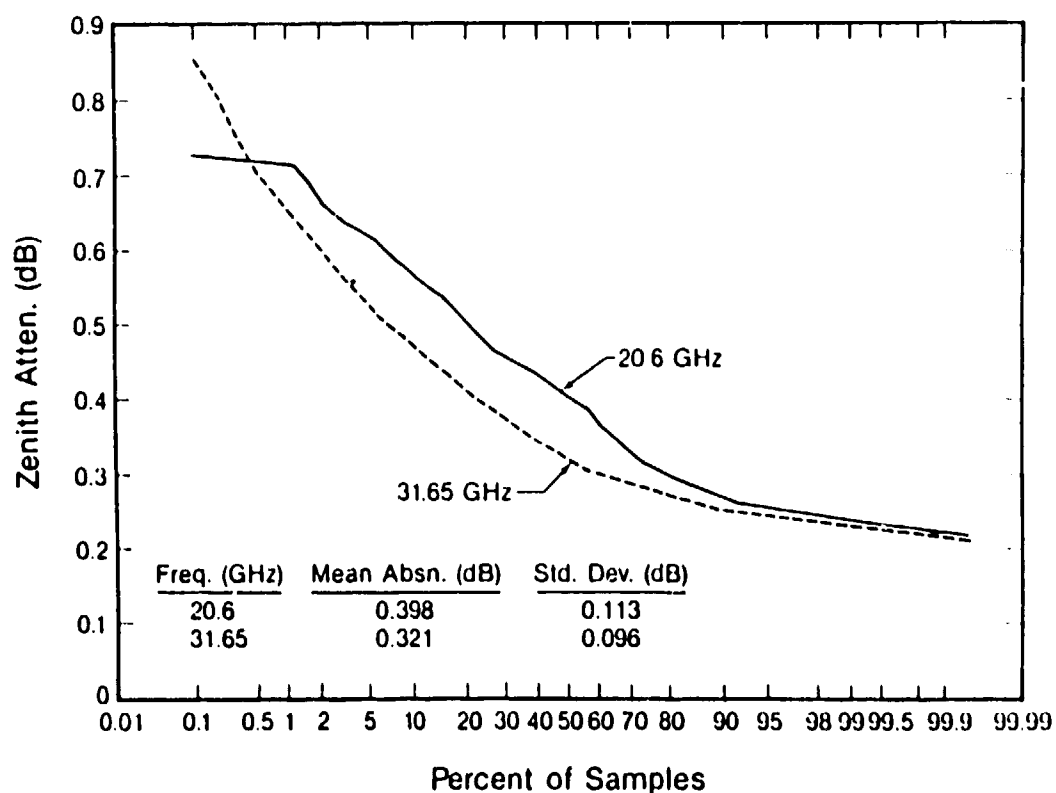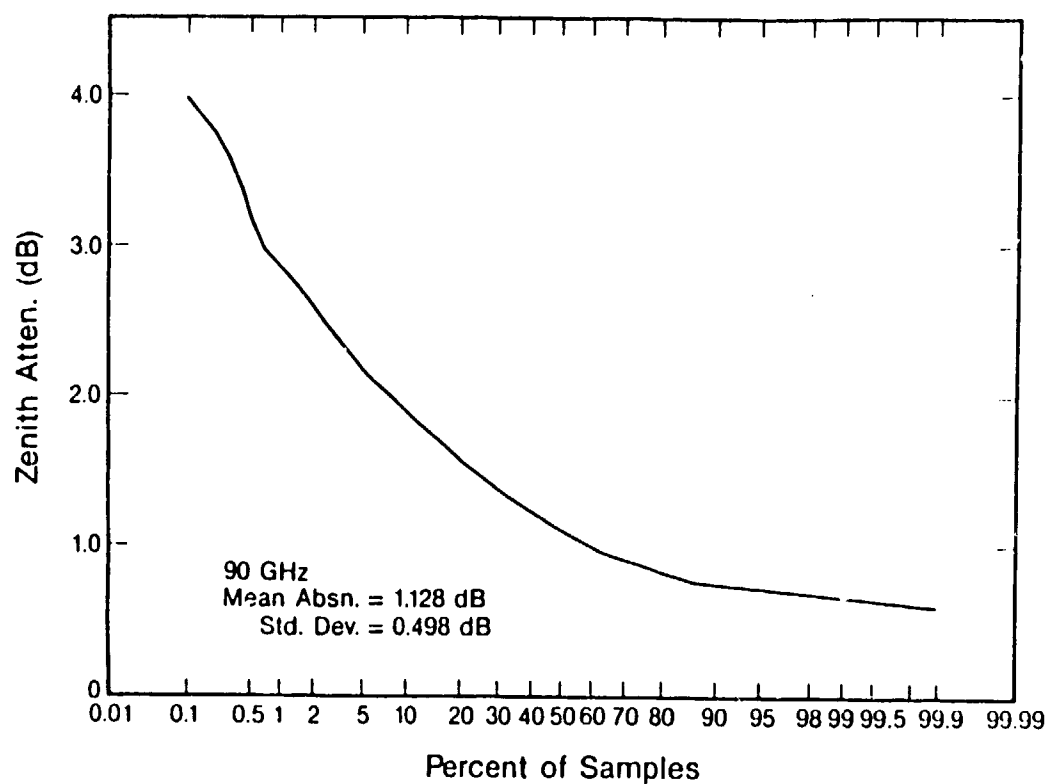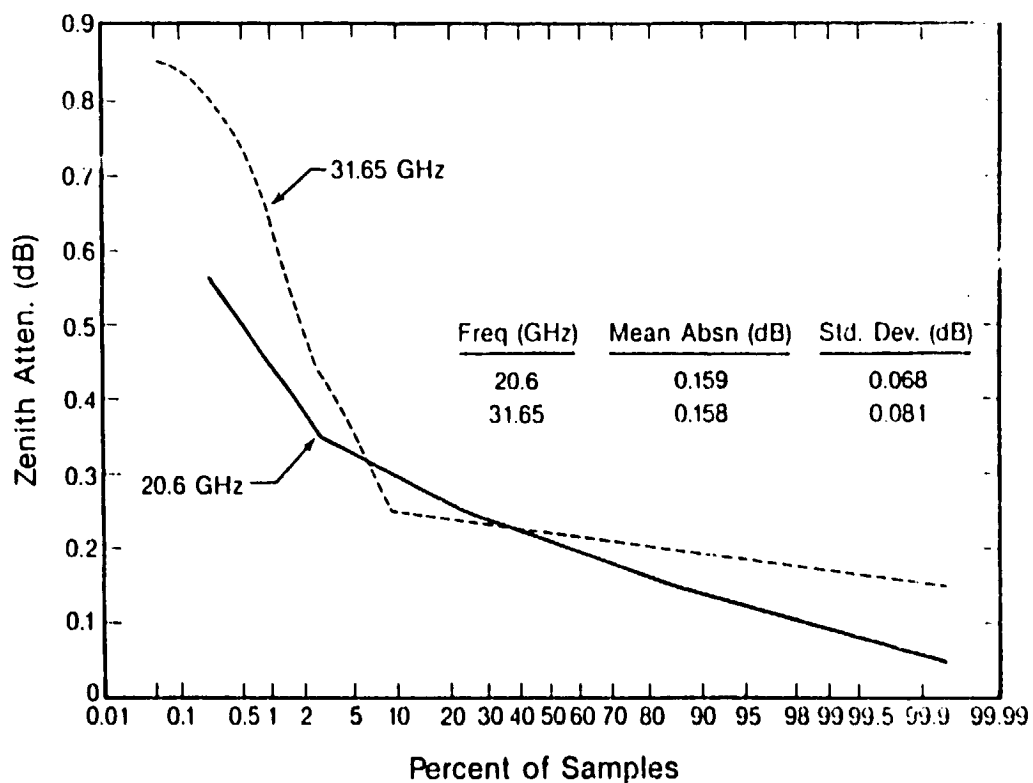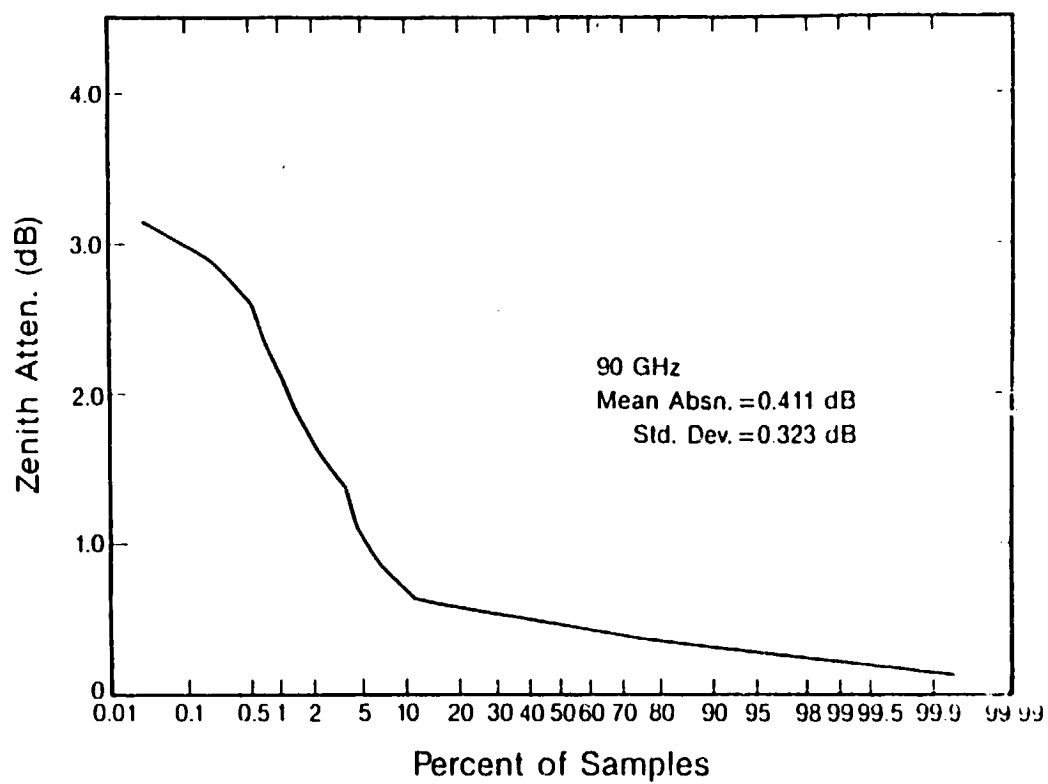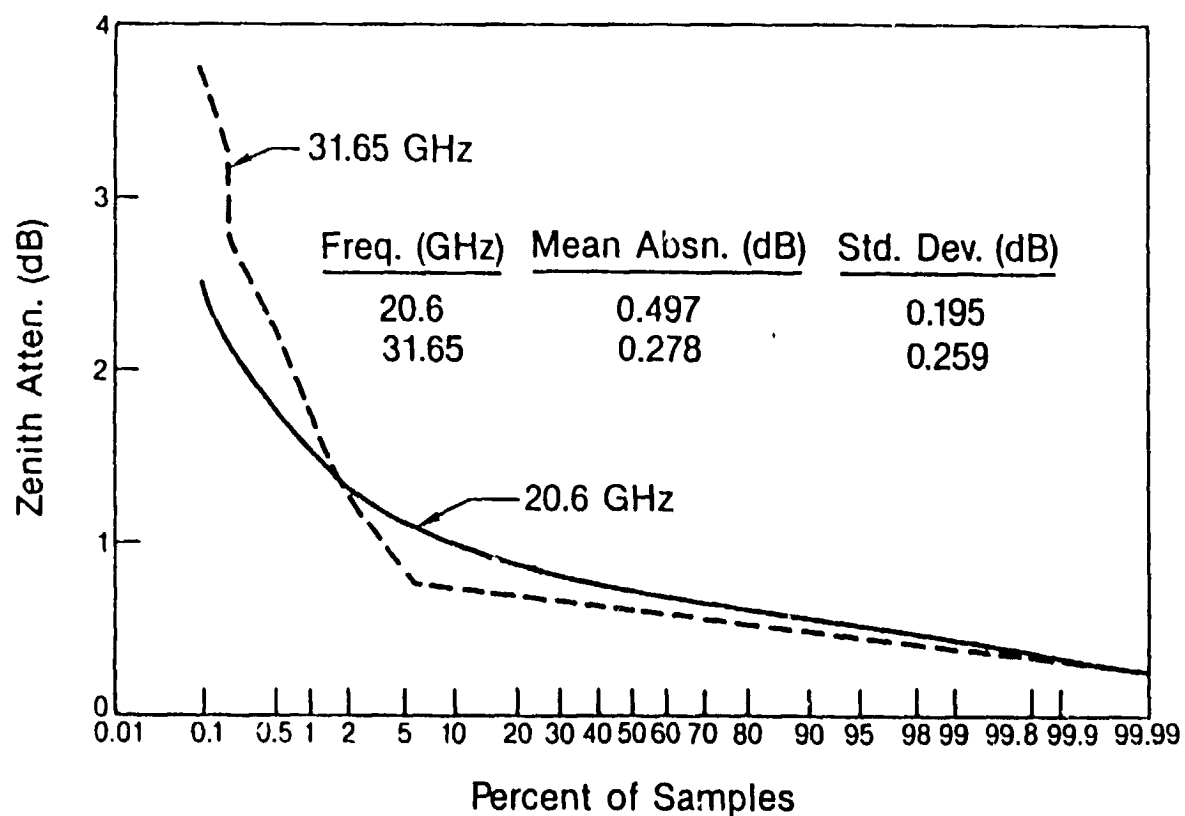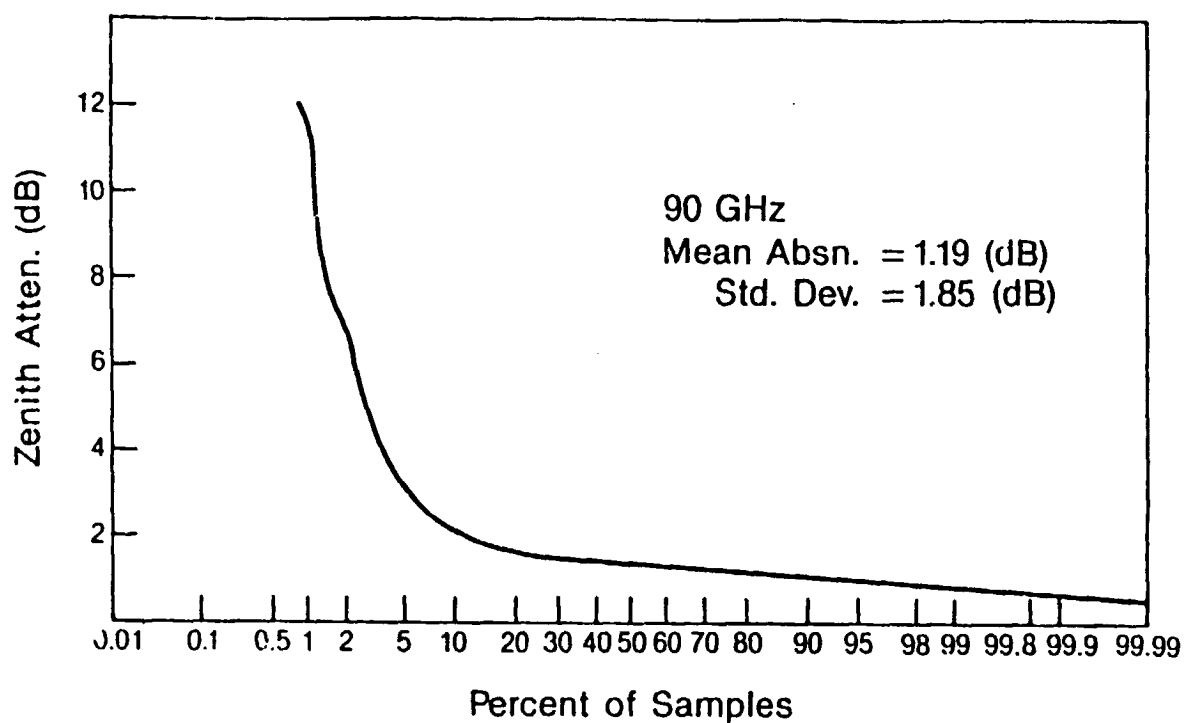
Fig. 4. Cumulative distribution of zenith attenuation measured by a three-channel radiometer at Denver, Colorado, August 1988. Data consist of 17792 2-min averages.

GHz and a Van Vleck-Weisskopf line shape to calculate the absorption. In addition, a "continuum" term, which accounts for contributions from lines above 1000 GHz as well as from possible dimer contributions, is added to the line contribution. We used data from a recent publication of Liebe and Layton (1987) to model H_2O absorption as a function of pressure, temperature, and water vapor pressure. Oxygen absorption was modeled using Liebe's formulas and computer software but with an updated version of O_2 interference coefficients given by Rosenkranz (1988). Our experience has been that the wing absorption at 20.6, 31.65, and 90.0 GHz is sensitive to the value of the O_2 interference coefficients. For example, the constants given by Liebe and Layton gave rise to calculated brightness temperatures at 90.0 GHz that differed from our measurement (and from calculations based on Rosenkranz's values) by about 5°. However, Liebe and Layton's constants gave slightly better agreement at 20.6 and 31.65 GHz. Thus, for very precise calculations, such as those required in remote sensing, further study may be necessary.

We calculated brightness temperature from radiosonde soundings of temperature, pressure, and water vapor, as a function of height. Since radiosondes do not measure cloud liquid, only data taken under clear conditions can be used for comparison. Tables 1-3 show mean and rms differences of measured and calculated brightness temperatures at SNI and DEN.

It is apparent from these tables that the agreement between theory and experiment in calculating clear air brightness temperatures is not completely satisfactory. Fairly substantial differences in the mean brightness temperature are present. However, the low standard deviations of the measurements for SNI and for DEN December suggest that some of the differences may be due to modeling the almost-constant dry term. The larger standard deviations and biases during DEN August suggest a problem in calculating absorption by water vapor. When comparing radiometer measurements with parameters derived from radiosondes, it should always be kept in mind that there are differences in the volumes of air sampled between the two instruments, and that the radiosonde itself is not a perfect instrument. Nevertheless, it seems that the mean differences between theory and experiment are significant, and that minor adjustments in parameters may be necessary.

Table 1. Comparison between measurements and calculations of brightness temperature at three frequencies at San Nicolas Island, California, July 1987 for a sample size = 14

	20.6 GHz	31.65 GHz	90.0 GHz
Mean difference (K)	2.88	1.80	1.39
Standard deviation (K)	0.65	0.32	1.16

Table 2. Comparison between measurements and calculations of brightness temperature at three frequencies at Denver, Colorado, December 1987 for a sample size = 22

	20.6 GHz	31.65 GHz	90.0 GHz
Mean difference (K)	1.68	1.08	0.46
Standard deviation (K)	0.72	0.33	0.97

Table 3. Comparison between measurements and calculations of brightness temperature at three frequencies at Denver, Colorado, August 1988 for a sample size = 37

	20.6 GHz	31.65 GHz	90.0 GHz
Mean difference (K)	3.85	0.47	0.95
Standard deviation (K)	1.44	0.81	2.25

5. OBSERVATIONS OF ATTENUATION FROM CLOUDS

In attempts to verify calculations of microwave emission and attenuation from clouds, a limitation has been that conventional radiosondes do not measure cloud liquid. Even if they did, the highly variable temporal and spatial characteristics of clouds would make comparisons difficult. With our radiometer design of equal beamwidths at all three channels, emission from a common volume can be observed simultaneously. If we can estimate oxygen and water vapor emission when clouds are present, we can then study relative cloud effects between the three channels. The procedure that we use is straightforward and seemingly effective. We first establish a lower cloud liquid threshold L_t for the presence of clouds, using the 20.6 and 31.65 GHz channels. In the past, this threshold has proved to be effective in separating clear and cloudy conditions. Next, we derive V from the dual-channel measurements. This determination of V has been extensively verified by comparison with radiosonde data, and indeed, is of the same order of accuracy as the radiosonde data. For data whose inferred L is less than L_t, that is, the "clear" set, we derive a regression relation between the measured absorption τ_{clr} and V:

$$\tau_{clr} = A + BV . \tag{3}$$

The frequency-dependent coefficients A and B in (3) have the physical significance of dry attenuation and the mass absorption coefficient. Finally, for the data whose inferred L is greater than L_t, that is, the "cloudy" set, we determine the cloud attenuation τ_{cld} by

$$\tau_{cld} = \tau - \tau_{clr}$$

$$\tau_{cld} = \tau - A - BV$$

$$= C + DL . \tag{4}$$

The coefficient D has the physical significance of the mass-absorption coefficient for cloud liquid, whereas if the procedure of subtracting clear attenuation from cloud attenuation were perfect, C would be zero. It should be understood that V in (4) has been derived from the absorptions in *cloudy* conditions measured at 20.6 and 31.65 GHz. We also derive L, but of course the accuracy of this determination has not been experimentally established, although theoretical estimates yield an accuracy of 0.0033 cm rms (Ciotti et al., 1987). Our results on the relationships between attenuation at the various frequencies are shown in Section 6; here in Tables 4-6 we present the results of our regression analyses to determine A, B, C, and D.

The values presented in these tables show that there is reasonable agreement between modeling and experiment, but also that, at Denver, in December, where the surface pressure is about 830 mb and the surface temperatures are frequently below zero, perhaps additional refinements are necessary. Since cloud liquid attenuation is sensitive to temperature, perhaps the disagreement between measurements and calculations at 90.0 GHz is significant. We intend to study this as more data become available.

6. PREDICTABILITY OF ATTENUATION BETWEEN VARIOUS FREQUENCIES

A fairly extensive amount of brightness temperature data at 20.6 and 31.65 GHz is available. Since data at 90.0 GHz are not plentiful, and since simultaneous measurements at all three frequencies are scarce, it is of interest to examine their between-channel predictability. Such considerations are important when attenuation is being estimated at various locations, and also for multifrequency remote sensing, when the consideration of dependent channels is of utmost importance. We determined regression relations between the various channels for clear, cloudy, and all conditions. The form of the linear regression is

$$\tau \text{ (dependent)} = c_0 + c_1 \tau_1 \text{ (independent)} + c_2 \tau_2 \text{ (independent)}. \tag{5}$$

The results of the regression analyses are shown in Tables 7-9.

It is clear from Tables 7-9 that there is a high degree of predictability between the channels, and that if care is taken to distinguish between clear and cloudy conditions, the correlation coefficients are greater than about 0.90 for the linear regression equations. However, since the coefficients vary considerably from location to location, and, for a fixed location, from season to season, extrapolation between different climates is not suggested.

Table 4. Regression coefficients, determined for three frequencies, for predicting zenith absorption τ (dB) from precipitable water vapor V (cm) or from integrated cloud liquid L (cm) |see Eqs. (3) and (4)|, San Nicolas Island, California, July 1987

Coefficient	20.6 GHz	31.65 GHz	90.0 GHz
Clear conditions			
(L < 0.0033 cm; N = 3417)			
A (dB)	0.0494	0.1281	0.2392
B (dB/cm)	0.1974	0.0787	0.3328
Corr. coeff.	0.9995	0.9811	0.9705
Clear conditions			
(calculated from 14 radiosondes)			
A (dB)	0.0812	0.1333	0.2387
B (dB/cm)	0.1759	0.0782	0.3488
Corr. coeff.	0.9797	0.9595	0.9518
Cloudy conditions			
(L > 0.0033 cm; N = 14168)			
C (dB)	0.0055	0.0073	0.0183
D (dB/cm)	3.5582	8.1057	45.2292
Corr. coeff.	0.9338	0.9662	0.9926

Table 5. Regression coefficients, determined for three frequencies, for predicting zenith absorption τ (dB) from precipitable water vapor V (cm) or from integrated cloud liquid L (cm) |see Eqs. (3) and (4)|, Denver, Colorado, December 1987

Coefficient	20.6 GHz	31.65 GHz	90.0 GHz
Clear conditions			
(L < 0.0033 cm; N = 12015)			
A (dB)	0.0499	0.1073	0.1881
B (dB/cm)	0.1894	0.0547	0.2575
Corr. coeff.	0.9967	0.8419	0.7681
Clear conditions			
(calculated from 937 radiosondes)			
A (dB)	0.0373	0.0821	0.1355
B (dB/cm)	0.1811	0.0643	0.3244
Corr. coeff.	0.9717	0.8205	0.9732
Cloudy conditions			
(L > 0.0033 cm; N = 2166)			
C (dB)	-0.0030	-0.0065	0.0136
D (dB/cm)	4.5601	10.3796	38.9128
Corr. coeff.	0.9999	0.9999	0.9728
Cloudy conditions			
(calculated from 500 radiosondes; cloud liquid determined from a cloud model)			
C (dB)	0.0028	0.0074	-0.0812
D (dB/cm)	4.5166	10.1190	52.9839
Corr. coeff.	0.9922	0.9951	0.9954

Table 6. Regression coefficients, determined for three frequencies, for predicting zenith attenuation τ (dB) from precipitable water vapor V (cm) or from integrated cloud liquid L (cm) [see Eqs. (3) and (4)], Denver, Colorado, August 1988

Coefficient	20.6 GHz	31.65 GHz	90.0 GHz
Clear conditions (L < 0.0033 cm; N = 15701)			
A (dB)	0.0286	0.0629	0.0165
B (dB/cm)	0.1771	0.0652	0.3284
Corr. coeff.	0.9973	0.9078	0.9531
Clear conditions (calculated from 2870 radiosondes)			
A (dB)	0.0337	0.0664	0.0463
B (dB/cm)	0.1751	0.0695	0.3560
Corr. coeff.	0.9997	0.9811	0.9786
Cloudy conditions (L ≥ 0.0033 cm; N = 2091)			
C (dB)	0.0076	0.0174	0.0949
D (dB/cm)	3.6747	8.4485	38.4164
Corr. coeff.	0.9999	1.0000	0.9975
Cloudy conditions (calculated from 2217 radiosondes; cloud liquid determined from a cloud model)			
C (dB)	0.0035	0.0066	0.0105
D (dB/cm)	3.7836	8.4907	47.3629
Corr. coeff.	0.9883	0.9907	0.9956

Table 7. Regression relations between absorption τ (dB) at 20.6, 31.65, and 90.0 GHz at San Nicolas Island, California, July 1987 [see Eq. (5)]

Regression relation	Statistics*		
Clear conditions (L < 0.0025 cm; N = 3417)			
$\tau(20.6) = -0.271 - 0.055\ \tau(90.0) + 0.266\ \tau(31.65)$	0.011,	0.986,	3.5
$\tau(31.65) = 0.086 + 0.141\ \tau(90.0) + 0.162\ \tau(20.6)$	.003,	0.995,	1.1
$\tau(90.0) = -0.332 - 0.107\ \tau(20.6) + 4.50\ \tau(31.65)$	0.015,	0.991,	2.2
Cloudy conditions (L > 0.0025 cm; N = 14162)			
$\tau(20.6) = -0.044 - 0.890\ \tau(90.0) + 5.72\ \tau(31.65)$	0.041,	0.933,	6.3
$\tau(31.65) = 0.093 + 0.172\ \tau(90.0) + 0.089\ \tau(20.6)$	0.005,	0.999,	1.4
$\tau(90.0) = -0.539 - 0.460\ \tau(20.6) + 5.73\ \tau(31.65)$	0.029,	0.998,	2.1
All data (N = 24129)			
$\tau(20.6) = -0.385 - 0.849\ \tau(90.0) + 5.43\ \tau(31.65)$	0.039,	0.939,	9.7
$\tau(31.65) = 0.087 + 0.175\ \tau(90.0) + 0.092\ \tau(20.6)$	0.005,	0.999,	1.6
$\tau(90.0) = -0.499 - 0.463\ \tau(20.6) + 5.64\ \tau(31.65)$	0.029,	0.998,	2.5

* Statistics are standard error of estimate, the correlation coefficient, and 100 times standard error of estimate divided by the mean.

Table 8. Regression relations between absorption τ (dB) at 20.6, 31.65, and 90.0 GHz at Denver, Colorado, December 1987 [see Eq. (5)]

Regression relation	Statistics*		
Clear conditions			
($L < 0.0033$ cm; N = 12105)			
$\tau(20.6) = -0.272 - 0.023\,\tau(90.0) + 3.57\ \ \tau(31.65)$	0.024,	0.889,	16.1
$\tau(31.65) = 0.076 + 0.136\,\tau(90.0) + 0.108\ \ \tau(20.6)$	.004,	0.972,	3.0
$\tau(90.0) = -0.396 - 0.252\,\tau(20.6) + 5.57\ \ \tau(31.65)$	0.026,	0.958,	8.2
Cloudy conditions			
($L > 0.0033$ cm; N = 2166)			
$\tau(20.6) = 0.055 + 0.047\,\tau(90.0) + 0.443\ \ \tau(31.65)$	0.028,	0.956,	12.6
$\tau(31.65) = 0.019 + 0.178\,\tau(90.0) + 0.455\ \ \tau(20.6)$	0.028,	0.981,	10.0
$\tau(90.0) = -0.207 + 0.892\,\tau(20.6) + 3.27\ \ \tau(31.65)$	0.122,	0.958,	13.3
All data			
(N = 14181)			
$\tau(20.6) = 0.084 + 0.139\,\tau(90.0) + 0.107\ \ \tau(31.65)$	0.040,	0.802,	25.2
$\tau(31.65) = 0.056 + 0.242\,\tau(90.0) + 0.014\ \ \tau(20.6)$	0.014,	0.984,	9.0
$\tau(90.0) = -0.229 + 0.279\,\tau(20.6) + 3.78\ \ \tau(31.65)$	0.056,	0.985,	13.7

* Statistics are as in Table 7.

Table 9. Regression relations between absorption τ (dB) at 20.6, 31.65, and 90.0 GHz at Denver, Colorado, December 1987 [see Eq. (5)]

Regression relation	Statistics*		
Clear conditions			
($L < 0.0033$ cm; N = 15701)			
$\tau(20.6) = 0.039 + 0.451\,\tau(90.0) + 0.236\ \ \tau(31.65)$	0.027,	0.968,	6.1
$\tau(31.65) = 0.056 + 0.177\,\tau(90.0) + 0.047\ \ \tau(20.6)$	0.012,	0.961,	5.6
$\tau(90.0) = -0.148 + 1.072\,\tau(20.6) + 2.125\ \ \tau(31.65)$	0.043,	0.978,	5.3
Cloudy conditions			
($L > 0.0033$ cm; N = 2091; $\tau(90.0) < 12$ dB)			
$\tau(20.6) = 0.046 + 0.024\,\tau(90.0) + 0.425\ \ \tau(31.65)$	0.067,	0.961,	8.3
$\tau(31.65) = -0.404 + 0.090\,\tau(90.0) + 0.995\ \ \tau(20.0)$	0.103,	0.972,	15.5
$\tau(90.0) = -1.141 + 2.119\,\tau(20.6) + 3.460\ \ \tau(31.65)$	0.637,	0.954,	22.1
All data			
(N = 17792; $\tau(90.0) < 12$ dB)			
$\tau(20.6) = 0.310 + 0.051\,\tau(90.0) + 0.487\ \ \tau(31.65)$	0.084,	0.878,	16.9
$\tau(31.65) = 0.006 + 0.182\,\tau(90.0) + 0.151\ \ \tau(20.6)$	0.047,	0.975,	17.2
$\tau(90.0) = -0.322 + 0.380\,\tau(20.6) + 4.347\ \ \tau(31.65)$	0.229,	0.974,	21.8

* Statistics are as in Table 7.

7. SUMMARY AND CONCLUSIONS

Measurements of atmospheric attenuation at 20.6, 31.65, and 90.0 GHz at climatically different locations and months (San Nicolas Island, California, July 1987, and Denver, Colorado, December 1987 and August 1988) have shown reasonable consistency between theory and experiment, both in clear air and during cloudy conditions. During clear conditions, comparisons between brightness temperatures that were measured and those that were calculated from on-site radiosondes, have average differences less than 3.9 K and standard deviations less than 2.3 K. The average differences are due (a) to uncertainties in calculating the wing contribution to absorption from the 60 GHz molecular band of oxygen; (b) to problems in calculating water vapor absorption; and (c) to uncertainties in calibrating the radiometers. The largest bias (3.9 K) was observed at 20.6 GHz during August 1988. The inability to account correctly for water vapor is a likely explanation for this bias. The ratios of cloudy attenuation values are reasonably consistent between the two locations. Probability distributions for attenuation were derived for the three climatologies and were both location and season dependent. Finally, we demonstrated that at a given location and season, the attenuations from any two of the channels could significantly predict the attenuation of the remaining one (correlation coefficients greater than 0.90). This predictability as based on stratifying the data sets into clear and cloudy samples and then using linear regression analysis.

8. FUTURE WORK

Three specific tasks will be accomplished during fiscal year 1989: (1) joint attenuation statistics (at 20.6 and 31.65 GHz) will be developed and analyzed for two locations of the Colorado Research Network. Denver and Platteville are the probable locations. (2) A 23.87 GHz radiometer has been purchased and will be both laboratory and field tested. Simultaneous measurements at 20.6, 23.87, 31.65, and 90.0 GHz will be compared with each other and with theoretical calculations based on radiosondes. (3) The three-channel transportable radiometer will be taken to another location—one that is climatically different from Denver, Colorado, and San Nicolas Island, California. Both clear and cloudy attenuation data will be collected there for analysis.

9. REFERENCES

Ciotti, P., E.R. Westwater, M.T. Decker, A.J. Bedard, and B.B. Stankov, 1987. Ground-based microwave radiometric observations of the temporal variation of atmospheric geopotential height and thickness. *IEEE Trans. Geosci. Remote Sensing*, GE-25, 600-615.

Hogg, D.C., F.O. Guiraud, J.B. Snider, M.T. Decker, and E.R. Westwater, 1983. A steerable dual-channel microwave radiometer for measurement of water vapor and liquid in the troposphere. *J. Appl. Meteorol.*, 22, 789-806.

Liebe, H.J., 1985. An updated model for millimeter wave propagation in moist air. *Radio Sci.*, 20, 1069-1089.

Liebe, H.J., and D.H. Layton, 1987. Millimeter-wave properties of the atmosphere: Laboratory studies and propagation modeling. NTIA Report 87-24, National Telecommunications and Information Administration, Boulder, CO. 1-80.

Rosenkranz, P.W., 1988. Interference coefficients for overlapping oxygen lines in air. *J. Quant. Spectrosc. Radiat. Transfer*, **39**, 287-297.

Westwater, E.R., and J.B. Snider, 1987. Microwave radiometer facilities at the Wave Propagation Laboratory. Proceedings of NAPEX XI, JPL D-4647, Jet Propulsion Laboratory, Pasadena, CA, 24-27.